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Operation of ultra-high voltage (>10kV) SiC IGBTs at elevated temperatures: benefits & constraints

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***Abstract*—State of the art TCAD simulation models are used to simulate the performance of ultra-high voltage (10-20 kV) SiC IGBTs in the temperature range 300-775 K. We show that unlike Si-based counterparts, ultra-high voltage SiC IGBTs stand to gain from the temperature rise if the limit is not exceeded. We show that whilst an operation at 375 K is highly promising to achieve the most optimum on-state characteristics from SiC IGBTs, no significant degradation in the on-state current and breakdown voltage alongside with negligible rise in leakage current is observed until 550 K. Therefore, ≥10 kV SiC IGBTs are highly promising for Smart Grid and HVDC.**

Keywords—SiC IGBT, Ultra-high voltage, Elevated Temperatures, HVDC and Smart Grid

I. INTRODUCTION

Owing to its superlative electrical properties, i.e., a wide bandgap of 3.25 eV, high critical field of ~2×10^6 V.cm^{-1}, high mobility of 950 cm^2.V^{-1}.s^{-1} and saturation velocity of ~2.2×10^7 cm.s^{-1}, 4H-SiC is of particular interest for high-voltage and high-temperature applications [1]. The 10 times increase in the critical field of 4H-SiC, when compared with that of Si, allows high-voltage devices to be fabricated on a significantly thinner and more-conducting blocking epilayer, which in turn significantly lowers the specific on-resistance [2-6]. In addition, because of the wide bandgap, the intrinsic carrier concentration remains low at high temperatures, being ~10^{10} cm^{-3} at 800 K, which is comparable to that of Si at room temperature [7, 8].

However, the advantage of having superior material properties is often overshadowed by the way the device operates. In particular, the strong dependence of both material properties and device operation physics upon temperatures can significantly alter device characteristics, which pose further challenges to designs of gate-drivers and converter topologies. In recent years, SiC IGBTs have attracted considerable attention for ultra-high voltage applications, most notably for low-carbon Smart Grid and HVDC, where elevated temperatures can lead to instability and thermal runaway problems [9-13].

In the case of Si IGBTs, the on-state current rating is chosen to restrict the IGBT temperature below the maximum junction temperature of 175 °C. The maximum junction temperature is less of an issue for SiC, and 300 °C is considered a safe operating temperature for devices, such as Schottky diodes, MOSFETs and JFETs [7, 8], as long as dedicated high temperature packages are used. However, the case of high temperature operation on ultra-high voltage SiC IGBTs has not been made yet.

A simultaneous high-voltage and high-temperature capability with a higher degree of stability to temperature variations is highly desirable in SiC IGBTs in order to offer a robust alternative to Si-based counterparts in the sector of power transmission and distribution. It is therefore imperative to assess the performance of ultra-high voltage SiC IGBTs at a wide range of temperatures and to identify possible range within which their operation might be compromised.

We have therefore examined the effect of different operating temperatures on the on-state performance of high-voltage (≥10 kV) SiC IGBTs. A very wide range of temperatures (i.e., 300-775 K) is included, and a particular emphasis is placed on key device characteristics, including the on-state current density, breakdown voltage and leakage current.

II. METHODOLOGY

2D-TCAD simulations are performed on ultra-high voltage SiC IGBTs using a simplified test-cell shown in

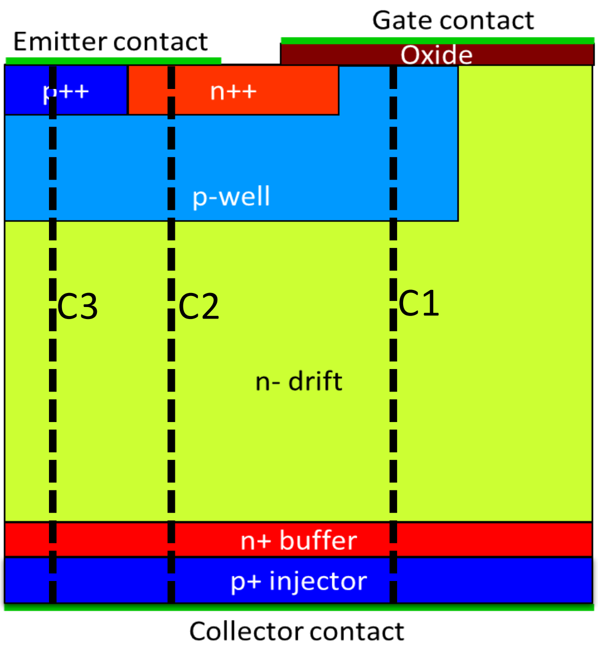

Fig. 1. An n-channel DMOS SiC IGBT test cell schematic.

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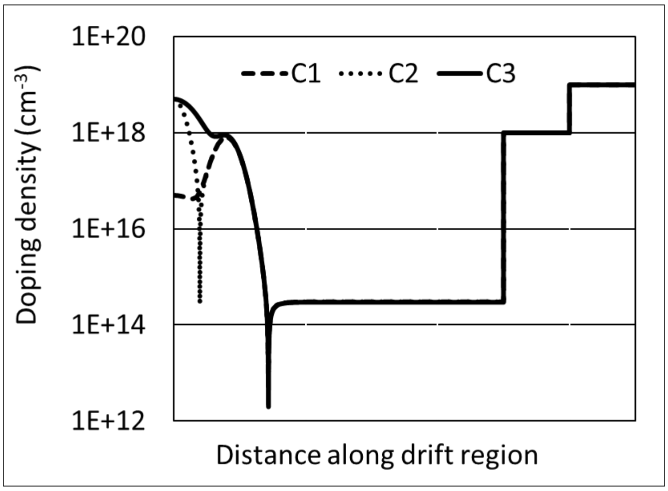

Fig. 2. Doping profiles along different cut-lines in Fig. 1 used to simulate ≥10 kV class SiC IGBTs.

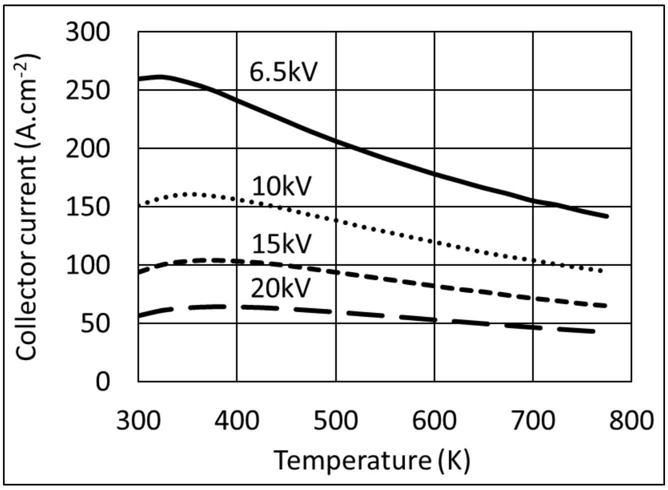

Fig. 4. Collector current density of ≥10 kV SiC IGBTs as a function of device temperature, when V_G=20 V and V_C=5 V

Fig.1. The test cell is an n-channel punch through IGBT design, which consists of doping profiles akin to those in Fig. 2. The drift region of test cell is simulated with the fixed doping concentration of 3e14 cm^{-3} and thicknesses of 50, 100, 150 and 200 µm, to achieve blocking voltages of 6.5, 10, 15, 20 kV, respectively.

To have a high-degree of carrier injection, a p^{++} injector with doping density of 1e19 cm^{-3} is utilized. The n^+ buffer doping concentration is set at 1e18 cm^{-3}, adequate to stop the electric field reaching the injector.

A retrograde p-well is utilized to achieve a robust control on threshold voltage and to eliminate the possibility of punch-through. Details are given in our previously published work [14]. The doping density at the surface of the retrograde p-well is 5e16 cm^{-3} and the gate oxide thickness is fixed at 50 nm, yielding a threshold voltage of 7-8 V. The doping profile along the cut line C1 shown in Fig 1 can be seen in Fig 2.

It is worth mentioning here that to achieve adequate conductivity modulation, an electron lifetime of 10 µs is utilized in simulations. The hole lifetime is considered to be the 1/5th of that of electron lifetime. Since low carrier lifetime is often achieved during bulk and epilayer growth of SiC, we have performed additional TCAD simulations with a reduced electron lifetime of 2.5 µs. We noted that the outcome of both set of simulations (i.e., with electron lifetime of 2.5 and 10µs) is very similar and thus not affecting the conclusion of this work. Furthermore, breakdown and leakage current characteristics are obtained using a background carrier concentration of 1e9 cm^{-3}.

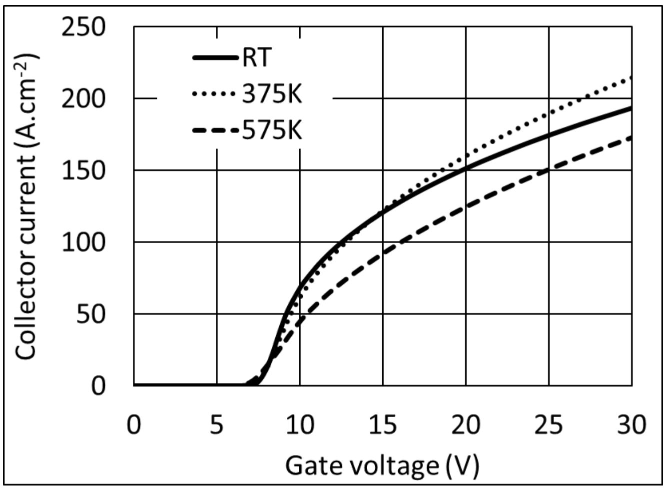

Fig. 3. Transfer characteristics of a 10 kV IGBT at RT, 375 K and 575 K, when collector voltage (V_C) is set at 5 V.

Impact ionization as a function of electric field is calculated using the Okuto-Crowell model for 4H-SiC. Doping and temperature dependency of carrier mobility is calculated using the Caughey-Thomas model. The lifetimes of carriers are modeled as a product of a doping-dependent, field-dependent and temperature-dependent factors, as embedded in Scharfetter model utilizing Shockley-Read-Hall (SRH) recombination mechanism.

Simulations consider the dependency of energy bandgap upon temperature and doping. Incomplete ionization of dopants in SiC is also considered. Nitrogen is modelled as a donor trap located 0.0709 eV from the conduction band and Aluminium modelled as an acceptor trap located 0.265 eV from the valance band. Extensive details regarding physics models and parameters used in simulations of 4H-SiC IGBTs can be found in our previous work [15,16].

III. Results and Discussion

Simulated transfer characteristics of a 10 kV SiC IGBT at room temperature (RT), 375 K and 575 K are shown in Fig. 3. We note that similar to Si IGBTs, the gate-threshold voltage (V_T) reduces with increasing temperature. However, for gate voltages higher than 15 V, the collector current density (I_C) is first increased with temperature (i.e., $I_{C,375K}$ > $I_{C,RT}$), followed by a decay with further increase in temperature (i.e., $I_{C,RT}$ > $I_{C,575K}$). For gate voltages in the range V_T–14V, $I_{C,RT}$ is higher than both $I_{C,375K}$ and $I_{C,575K}$. In the case of Si IGBTs, for gate voltages higher than V_T, the collector current consistently reduced with increase in temperature.

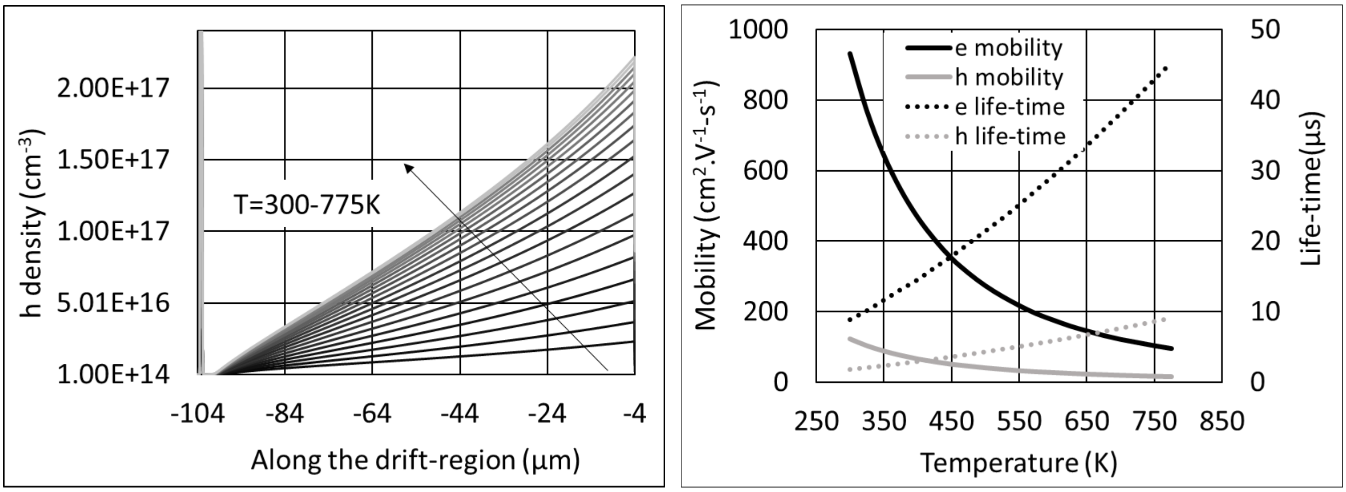

Fig. 5. Hole-injection along the drift region in a 10kV SiC IGBT, as a function of temperature, when V_G=20V and V_C=5V (left). Electron (e) and hole (h) mobilities and lifetimes in a 10kV SiC IGBT as a function of temperature when V_G=20V and V_C=5V (right). Simulation results are obtained using an electron lifetime of 10μs.

The collector current density in the extended temperature range for blocking voltages of 6.5, 10 15 and 20 kV is depicted in Fig. 4. We note that for investigated blocking voltages, consistent with transfer characteristics, a mild increase in temperature is benefitting the on-state current of SiC IGBTs, being the highest at 375 K. For temperatures higher than 375 K, the IGBT current begins to decrease. This constitutes an initial negative temperature coefficient of resistance with temperature up to until 375 K and a positive temperature coefficient for resistance as the temperature becomes higher than that. The latter is an important finding for achieving parallel operation of multiple cells in a chip or multiple chips in a power module. It means that any thermal runaway can be avoided, if the package and the module can allow temperatures higher than 375 K.

The behavior of SiC IGBT output current can be attributed to a complex relationship between temperature-dependent injection efficiency, carrier incomplete ionization, lifetime and mobility. As shown in Fig. 5, the hole injection significantly increases with temperature. A three order of magnitude difference in the hole density near the p+ injector is evident when the temperature increased from 300 K to 775 K. Carrier lifetimes also increase with temperature, however, carrier mobilities have a significant reduction. Electron and hole mobilities reduced from 950 $cm^2.V^{-1}.s^{-1}$ and 125 $cm^2.V^{-1}.s^{-1}$ to 96 $cm^2.V^{-1}.s^{-}1$ and 16 $cm^2.V^{-1}.s^{-1}$, respectively, for the temperature range 300-775 K. The change in carrier mobilities is even steeper in the temperature range 300-400 K. Carrier mobilities at 400 K are smaller than half of their respective room temperature values, greatly suppressing the advantage of enhanced injector efficiency and carrier lifetime. In other words, the onus lies with achieving the best trade-off between injector-efficiency, carrier lifetime and mobility to see the advantages of elevated temperatures in SiC IGBTs operation.

Temperature is known to improve the carrier mean-free path, and reduce the avalanche coefficients despite the increased carriers thermal ionization, which in-turn improves

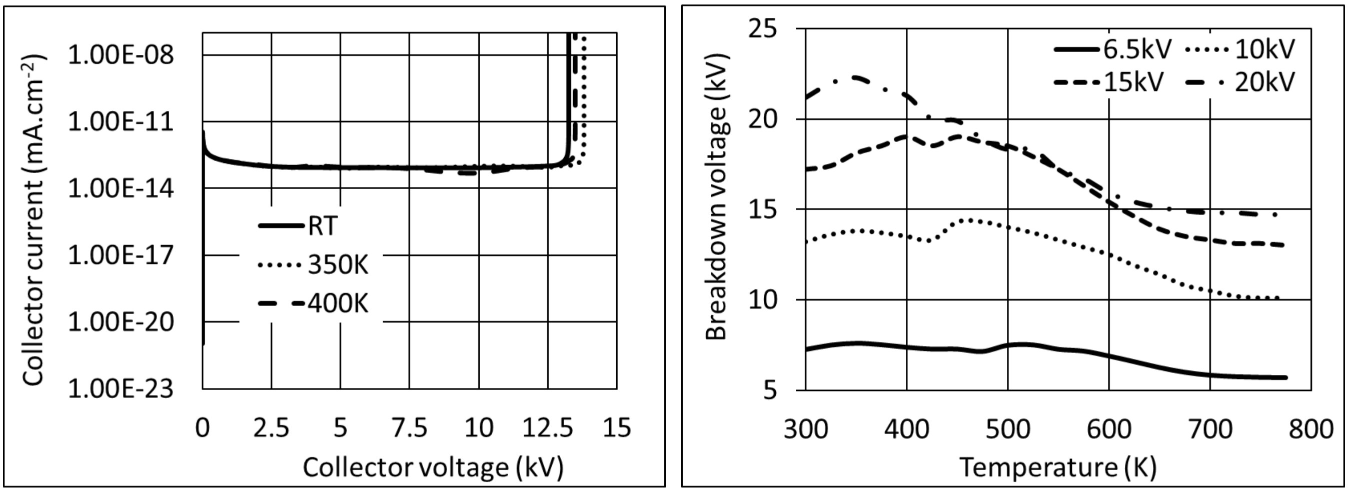

Fig. 6. Breakdown characteristics of a 10 kV SiC IGBT at RT, 325 K and 575 K (left). Breakdown voltage of ≥10 kV SiC IGBTs in extended temperature range (right).

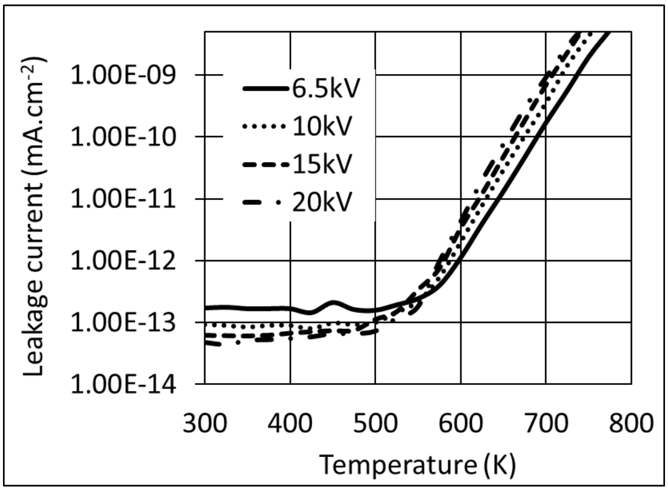

Fig. 7. Leakage current of ≥10 kV SiC IGBTs in the OFF state as a function of temperature.

the blocking capability of a unipolar device. However, significant bipolar effects (i.e., the transistor gain., and the a high-degree of electron-hole pairs concentration near the p-well/drift junction), further augmented by the reduced p-well/drift junction voltage at high-temperatures, can trigger a premature breakdown in IGBTs.

As shown in Fig. 6, the breakdown voltage of a 10 kV SiC IGBT at room temperature is higher than 400 K but lower than 350 K, arising due to the combined effect of prolonged mean-free path and the increased bipolar effect at elevated temperatures.

The variation in breakdown voltage in the extended temperature range is further examined for SiC IGBTs with blocking ratings of 6.5, 10, 15 and 20 kV. Each data set consists of multiple peaks, which can be attributed to the dependence of breakdown voltage on both mean-free path and the bipolar effect as temperature increases. Nevertheless, it is important to note that the breakdown voltage for investigated IGBTs is broadly unaffected by temperature until ~500 K, reducing afterwards.

A qualitative assessment of leakage current characteristics of SiC IGBTs as a function of temperature is also performed. As shown in Fig. 7, the leakage current reduced with the blocking capability of IGBT. A high blocking capability requires a more resistive drift region, i.e., thick or/both low-doped epilayer, which results in reduced ON as well as a reduced OFF state current. Nevertheless, it is noteworthy that the leakage current remains low until 550K and begins to rise considerably afterwards.

IV. Conclusion

In conclusion, we have extensively studied the performance of ultra-high voltage class (≥10 kV) of SiC IGBTs at elevated temperatures. We show that the ultra-high voltage range of SiC IGBTs is benefiting from elevated-temperatures due to a complex interplay of bipolar effects and SiC material properties. In particular, we show that the SiC IGBT operation in the range 300-475 K is satisfactory with negligible impact upon the blocking voltage capability and leakage current, whilst 375 K being very promising to achieve the most optimum on-state operation. Therefore, ≥10 kV SiC IGBTs are expected to work reliably and with highly promising performance when used in Smart Grid and HVDC.

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